Power System Security Enhancement by NARX ANN Model Based Interline Power Flow Controller (IPFC)

Harsh R. Mankar[a] and Vinod K. Chandrakar[b]
Dept. of Electrical Engineering, G H Raisoni College of Engineering Nagpur, India

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Abstract: Ensuring stability and reducing oscillations are critical for the reliable operation of modern power systems. One effective approach to achieve these goals is through the use of an Interline Power Flow Controller (IPFC). This paper focuses on the design of a PI-based controller for two Static Synchronous Series Compensators (SSSCs), employing a unified and simultaneous control method across multiple transmission lines. The main objective is to enhance the system's initial first peak stability, shorten the settling time, and mitigate oscillations in large and complex power networks. The control mechanism for the voltage-source converter-based SSSC aims to improve transient performance under various operating scenarios. The study compares the performance of the PI-based IPFC with an NARX ANN Model based IPFC, demonstrating the enhanced stability provided by the ANN approach during large and sudden disturbances. The effectiveness of both control strategies is validated in the MATLAB environment.

1 INTRODUCTION

Power systems worldwide are increasingly facing stability challenges due to the integration of renewable energy sources, rising demand, and more complex interconnections. Oscillations, a natural aspect of these dynamic systems, can cause significant disruptions if not properly managed. Traditional methods for damping these oscillations often fall short in addressing the needs of modern, complex, and variable power grids (Hingorani and Gyugyi, 2000), (Padiyar, 2007), (Zhang, Rehtanz, et al. , 2006), (Kundur, 1994). The Interline Power Flow Controller (IPFC), a component of Flexible AC Transmission System (FACTS) technology, offers a versatile and efficient solution to these challenges. As a multifunctional FACTS device, the IPFC is capable of controlling power flow and enhancing system stability. It uses multiple Voltage Source Converters (VSCs) connected through a common DC link, allowing it to manage power flow across multiple transmission lines simultaneously. This capability makes the IPFC particularly effective at reducing oscillations and improving overall system stability (Dhurvey, Chandrakar, et al. , 2011), (More, Chandrakar, et al. , 2016), (Dhurvey, Chandrakar, et al. , 2016), (Dhurvey, Chandrakar, et al. , 2016), (Dhurvey, Chandrakar, et al. , 2016), (Dhurvey, Chandrakar, et al. , 2019).

The IPFC's ability to suppress oscillations comes from its dynamic power flow management across several transmission lines. By adjusting the voltages in the series compensators, it can influence power transfers and phase angles, effectively mitigating oscillations. Its rapid response and adaptability give the IPFC a significant advantage over traditional damping methods, particularly in complex and variable power networks (Belwanshi, Chandrakar, et al. , 2011), (Bhande, Chandrakar, et al. , 2022), (Dhurvey, Chandrakar, et al. , 2019), (Dhurvey, Chandrakar, et al. ,). Additionally, incorporating a NARX (Nonlinear Autoregressive with Exogenous Inputs) Artificial Neural Network (ANN) enhances the IPFC's performance. The NARX ANN provides an advanced control mechanism by accurately predicting system behaviour and improving the IPFC's ability to handle large disturbances and

[a] https://orcid.org/0009-0008-9030-5989
[b] https://orcid.org/0000-0002-0912-7281

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varying operating conditions (Chandrakar, Dhurvey, et al. , 2018).

The effective damping of oscillations with Interline Power Flow Controllers (IPFCs) depends on advanced control systems that continuously monitor key parameters such as voltage, current, and power flow. IPFCs can quickly adjust the outputs of Voltage Source Converters (VSCs) to provide the necessary compensating voltages. By optimizing power flow, IPFCs improve the efficiency of existing transmission infrastructure, thereby increasing system capacity without the need for new transmission lines. Despite their benefits, IPFCs face challenges such as complex control requirements, integration difficulties, and high maintenance needs (Bhande, Chandrakar, et al. , 2022), (Bhande, Chandrakar, et al., 2023). (Chandrakar, Kothari, et al., 2004), (Tadurwar, Chandrakar, et al. , 2021).

The firing control of VSCs is critical to achieving the IPFC's goal of efficient power flow management. PI-based controllers are commonly used in the industry to manage power flow in large power systems during transient conditions. However, their performance can degrade under significant system changes, requiring precise tuning of the PI parameters to maintain optimal performance. The performance of PI based controllers deteriorates under large and sudden variation of operating condition in large power system. The PI constants Kp, Ki are fixed for one operating condition therefore under varying operating condition PI performance not satisfactory hence there is need of replacement by ANN Based controllers.

The Multilayer feedforward network is commonly used algorithm in place of PI controller. The large power system with IPFC is non-linear system therefore NARX ANN Model deals better as compared to multilayer feedforward network.

This paper presents the design of a PI-controlled IPFC and compares it with an NARX ANN Model based IPFC, both aimed at managing two Static Synchronous Series Compensators (SSSCs) on different transmission lines. The proposed controllers are designed to improve the initial peak deviation of generator rotor speed during sudden and large disturbances and to reduce oscillations under transient conditions. The performance of these controllers is evaluated under various transient conditions and load scenarios in complex network configurations using MATLAB simulations. The results show that the ANN-based IPFC significantly enhances damping effectiveness and successfully meets its objectives.

1.1 IPFC Modeling

The IPFC is made up of several Static Synchronous Series Compensators (SSSCs) that are interconnected through a shared DC link, as illustrated in Figure 1. Each SSSC helps manage reactive power compensation for its specific transmission line. Furthermore, the system can facilitate the transfer of real power between lines, enabling power to be shifted from a less loaded line to a more heavily loaded one using the common DC link.

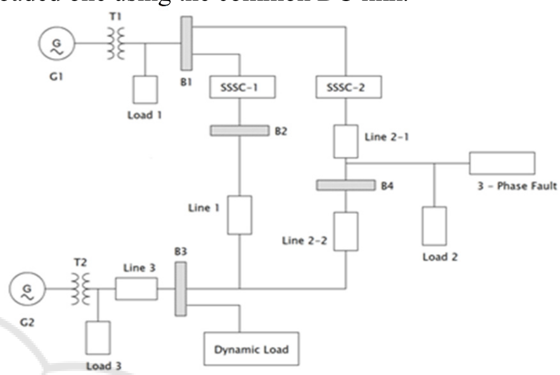

Figure 1: Interline Power Flow Controller with Sampled Power System.

Figure 2 depicts the maximum output voltages of the two inverters as represented by the circle. The central voltage compensation line, aligned with V1 and passing through the circle's center, represents the voltages that neither supply nor absorb active power from the transmission lines. On the right side of this central line, the voltage compensation lines correspond to voltages that deliver active power to the transmission line. On the left side, these lines indicate voltages that draw active power from the transmission line.

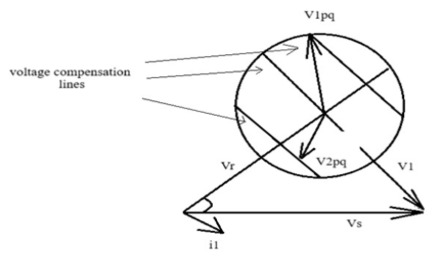

Figure 2: Vector diagram of IPFC.

The mathematical model is developed with the assumption that no power is exchanged through the DC link. By replacing Vsein with Isein in parallel with the transmission line and neglecting the resistances of the transmission line and series coupling transformers, the current source can be expressed as follows (Belwanshi, Chandrakar, et al. , 2011)].

ISeinjbSein (1)

Complex power injected at 1st bus is

Sinj1 $\sum_{n=2,3} V1$ (-ISein)* (2)

Sinj,1 $\sum_{n=2,3} V1$ (jbseinVsein)* (3)

Active & reactive power injection at 1st bus are

Pinj,1 = Re (Sinj,1) = $\sum_{n=2,3} V1$VSein b Sein Sin (θ1 – θSein)) (4)

Qinj,1 = Im = - $\sum_{n=2,3} V1$ VSein bSein cos (θ1 – θSein))

Similarly, complex power, active power & reactive power injection at nth bus (n=2,3) is

Sinj,n = Vn (ISein)* = Vn (-jbSein VSein)*

Pinj,n = Re (Sinj,n) = -Vn VSein bSein sin (θn – θSein)

Qinj,n = Im (Sinj,n) = Vn VSein bSein cos(θn – θSein) (5)

2 CONTROL SCHEME FOR IPFC

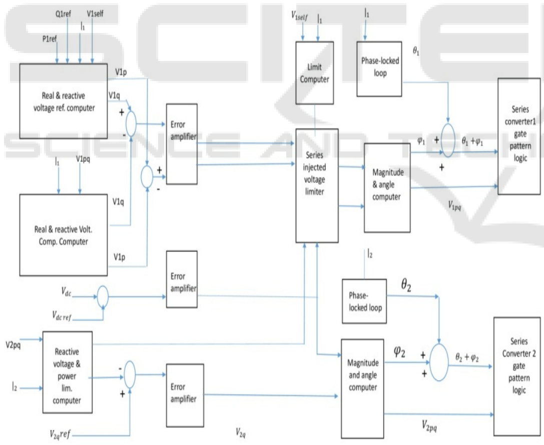

Figure 3: Scheme for IPFC Control.

In the control configuration shown in Figure 3, converter 1 is the primary converter, and converter 2 operates as the secondary converter, supporting the operation of converter 1. Converter 2 defines the active power limit for converter 1. Each converter generates its own phase angles using a phase-locked loop, which are then compared with the phase angle of the injected voltage. This comparison results in the generation of firing pulses for both converters.

2.1 System Model

In the control configuration illustrated in Figure 1, SSSC 1 acts as the primary converter, and SSSC 2 supports it as the secondary converter. SSSC 2 establishes the active power limit for SSSC 1. Both converters utilize individual phase-locked loops to generate their respective phase angles, which are then compared with the phase angle of the injected voltage. This comparison leads to the creation of firing pulses for both converters.

3 ANN BASED IPFC

Figure 4 illustrates the architecture of the multilayer feedforward network. This network is designed with two input neurons, which receive the measured voltage and reference voltage at the IPFC location. The hidden layers process these input signals, and at the output layer, a single neuron generates the firing signal for the pair of SSSCs.

Additionally, a Nonlinear Autoregressive with Exogenous Inputs (NARX) Artificial Neural Network (ANN) is incorporated into the system. The NARX ANN enhances the network's ability to predict and adapt to dynamic changes in the power system, improving the overall control and performance of the IPFC by capturing nonlinear relationships and time-dependent behavior in the system's operation. The defining equation for the NARX model is,

$$y(t) = f(y(t-1), y(t-2),\ldots, y(t-n_y), u(t-2),\ldots, u(t-n_u)) \quad (6)$$

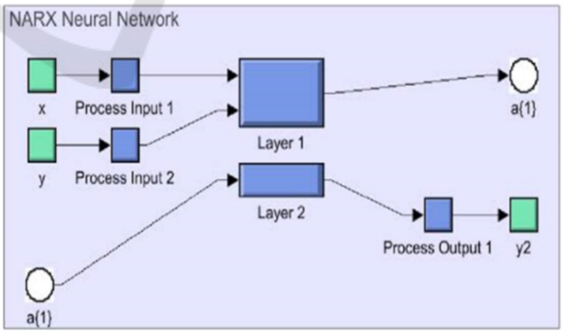

Figure 4: NARX Neural Network.

Figure 5 illustrates the design of a PI controller combined with a NARX ANN controller, implemented in the MATLAB environment.

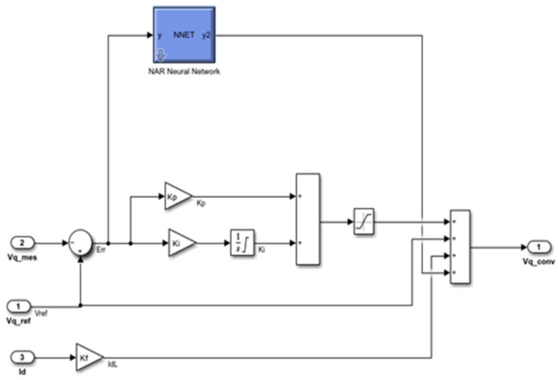

Figure 5: NARX ANN Model.

4 SIMULATION RESULT

The test system response under three phase fault at bus number 4 for the 0.11 second. Simulation response shown in fig. 6.

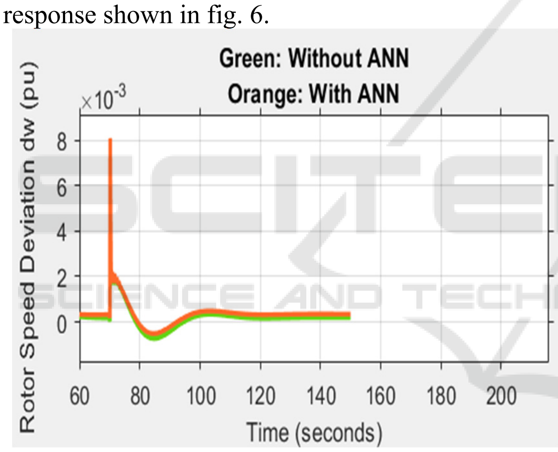

Figure 6.1: Rotor Speed Deviation dw (pu).

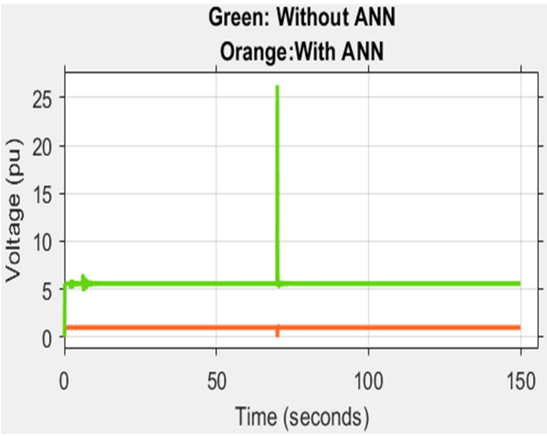

Figure 6.2: Voltage (pu).

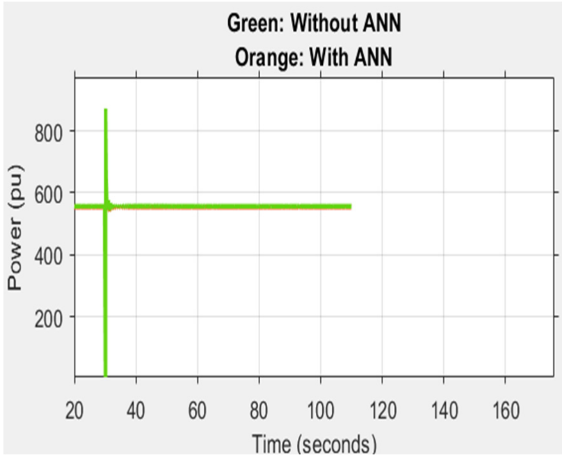

Figure 6.3: Power (pu).

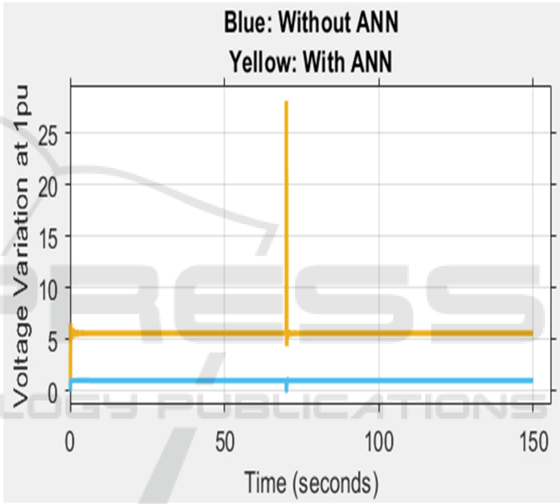

Figure 6.4: Reactive Power Variation (pu).

The figures 6.1, 6.2, 6.3, 6.4 shows the simulation response under disturb condition of the sampled power system indicates that the first peak significantly reduced by ANN Model and the oscillations are also reduced.

5 CONCLUSION

The study clearly highlights the advantages of using NARX Model based Interline Power Flow Controllers (IPFCs) over traditional PI-based controllers in improving power system stability. The ANN-based IPFC not only enhances the damping of power system oscillations but also reduces the first peak deviation and settling time during transient disturbances.

Simulation results show that the ANN-based control strategy provides a more flexible and dynamic response to system disturbances, enabling efficient power flow management across multiple transmission lines.

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